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Cavity Lifetime Phase-Shift Method for Sensitive Reflectance Measurements at Mid-infrared Wavelengths

14 December 1981

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ABSTRACT

The cavity phase shift method can measure high reflectances on spherical surfaces with good spatial resolution. Successful demonstration at 2.9-μm wavelength is described.

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FIGURES

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I. INTRODUCTION

The major objective of this project is a proof-of-principle demonstration of the Cavity Phase Shift method for measuring high reflectances in the mid-infrared wavelength region (2.6 - 4.2 μm). Specifically, these tests have been conducted at an HF laser wavelength of 2.9 μm. The Cavity Phase Shift (CAPS) method (described in detail in Ref. 1) is important to defense technologies because of the growing interest in very-high-reflectance mirrors of large sizes in high-energy lasers and a similar interest in large-aperture optics in future satellite systems. CAPS has the capability to evaluate the reflectance, or, because of its high sensitivity, the scattering/absorption losses in these types of optical elements. With good spatial resolution, the CAPS approach is able to provide point-by-point evaluation of a large-surface mirror. The spatial uniformity in optical properties of these large elements becomes an increasingly significant issue as sizes grow. The ability of CAPS to monitor spatial and temporal variations, with relative simplicity in setup and instrumentation, permits the method ultimately to be used in field-operable or in-situ situations, such as the study of a flux-loaded laser mirror or the maintenance of quality control in the fabrication of optical coatings.

The approach here has already been used at visible to near-infrared (8800 Å) wavelengths while supporting work on new chemical lasers (Ref. 1). One outstanding result is that high-quality mirrors at 8742 Å were newly developed with use of the method, and were measured to be 0.99975 in reflectance with the same CAPS method (Ref. 2).

Proof-of-principle at the desired wavelength is essential before there can be further investment by MOIE sources or other funding agencies. There are already identified issues in the High-Energy Laser Program that only this method can easily address. One current approach in high-energy lasers is the use of classical ellipsometry to determine relative reflectances and relative phase shifts in the electric field upon reflection from the mirror at limited spatial resolution (Ref. 3).

The Aerospace approach differs from all others in that it provides a direct measurement of absolute reflectance at the two possible linear polarizations, with the high spatial resolution determined by a cavity mode. Two methods devised by others competitive in sensitivity actually detect mirror losses, from which reflectance is deduced (Refs. 4 and 5). These two other methods require the movement of crucial mirrors and other elements of the optical train during the measurement; the Aerospace method does not. The other methods appeared constrained to the laboratory environment because of complexity, sophistication or delicacy.

II. EXPERIMENT

The CAPS method consists of making the mirror with unknown high reflectance part of an interferometric optical cavity structure of very high Q (Fig. 1). As a result of a large number of multiple passes by radiation off the element of unknown reflectance, a high sensitivity and great accuracy can be exploited in measuring the unknown reflectance or slight changes in the unknown reflectance. The radiation source is an intensity-modulated laser beam passed through the interferometric structure by transverse mode matching. A phase shift in the sine wave modulation of intensity yields a direct measurement of the unknown reflectance. The phase shift is determined by use of a phase-sensitive lock-in amplifier that detects the difference between the reference phase without cavity (dotted line, Fig. 1) and then the phase shift with cavity (heavy line). Because the method detects a phase difference and not intensity changes, the reference phase apparatus, which consists of four simple mirrors, does not require a crucial alignment and can be flipped in and out of the path. The unknown high-reflectance R_2 is simply related to the phase shift Φ by (Ref. 1)

$$\tan \phi = \frac{4\pi fL}{C}\left(\frac{R_1R_2}{1 - R_1R_2}\right)$$

where f is the modulation frequency; L, interferometer length; c, speed of light within the cavity; and R_1, a known previously determined high reflectance. The ability to vary f or L provides techniques for data analysis. With a given three-mirror set and two-mirror test cavity, the reflectances of all three can be determined absolutely, two at a time.

This report describes work extending the CAPS method to the mid-infrared region between 2.7 and 4.0 μm. The high brightness source used is an HF cw laser at the 1-to-5-watt power level on a given lasing transition. In this series the resonator includes a 1264-cm radius-of-curvature mirror and a diffraction grating in Littrow position, 93 cm from the mirror. The active

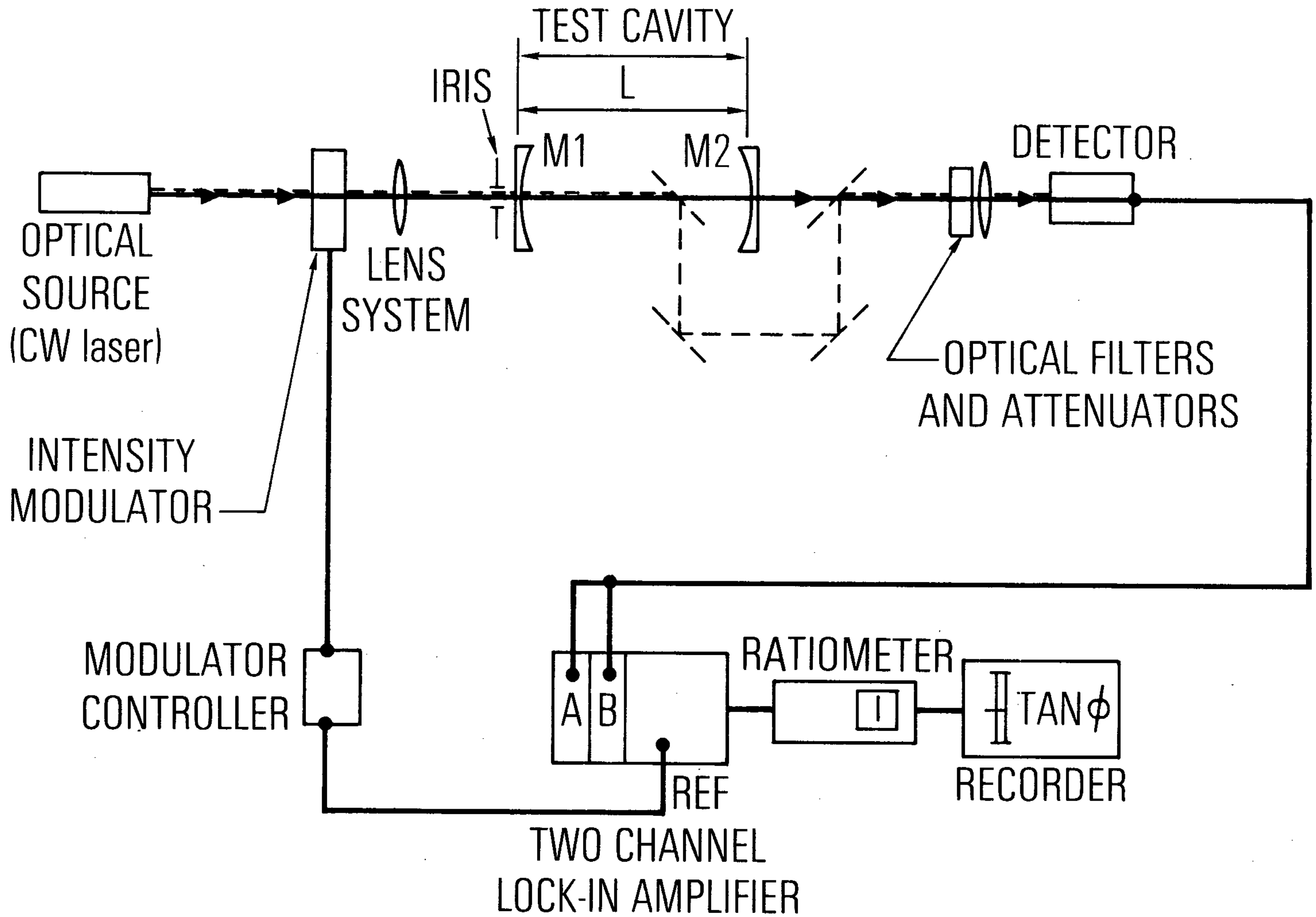

Fig. 1. Schematic of the Cavity Phase Shift (CAPS) Method

gain region is a 30-cm wide subsonic flow. The laser beam is passed through a germanium crystal acousto-optic modulator capable of intensity sine wave modulations from DC beyond 1-MHz frequencies. The beam is then mode-matched into a two-mirror optical test cavity. A liquid-nitrogen-cooled indium antimonide detector receives the phase-shifted laser signal. The optical layout is shown as a schematic in Fig. 2 and as a photograph in Fig. 3.

The test mirrors for this demonstration have transmitting silicon substrates polished to 200-cm radii of curvature at 2.5-cm diameter apertures. The substrates are dielectric-coated in one batch for high reflectances between 2.5 and 3.1 μm; they are antireflection coated on their backs. The work has been done with the HF $P_2(8)$ transition, 2.911-μm wavelength. This position was chosen to minimize the effects of atmospheric water vapor absorption prevalent in this region.

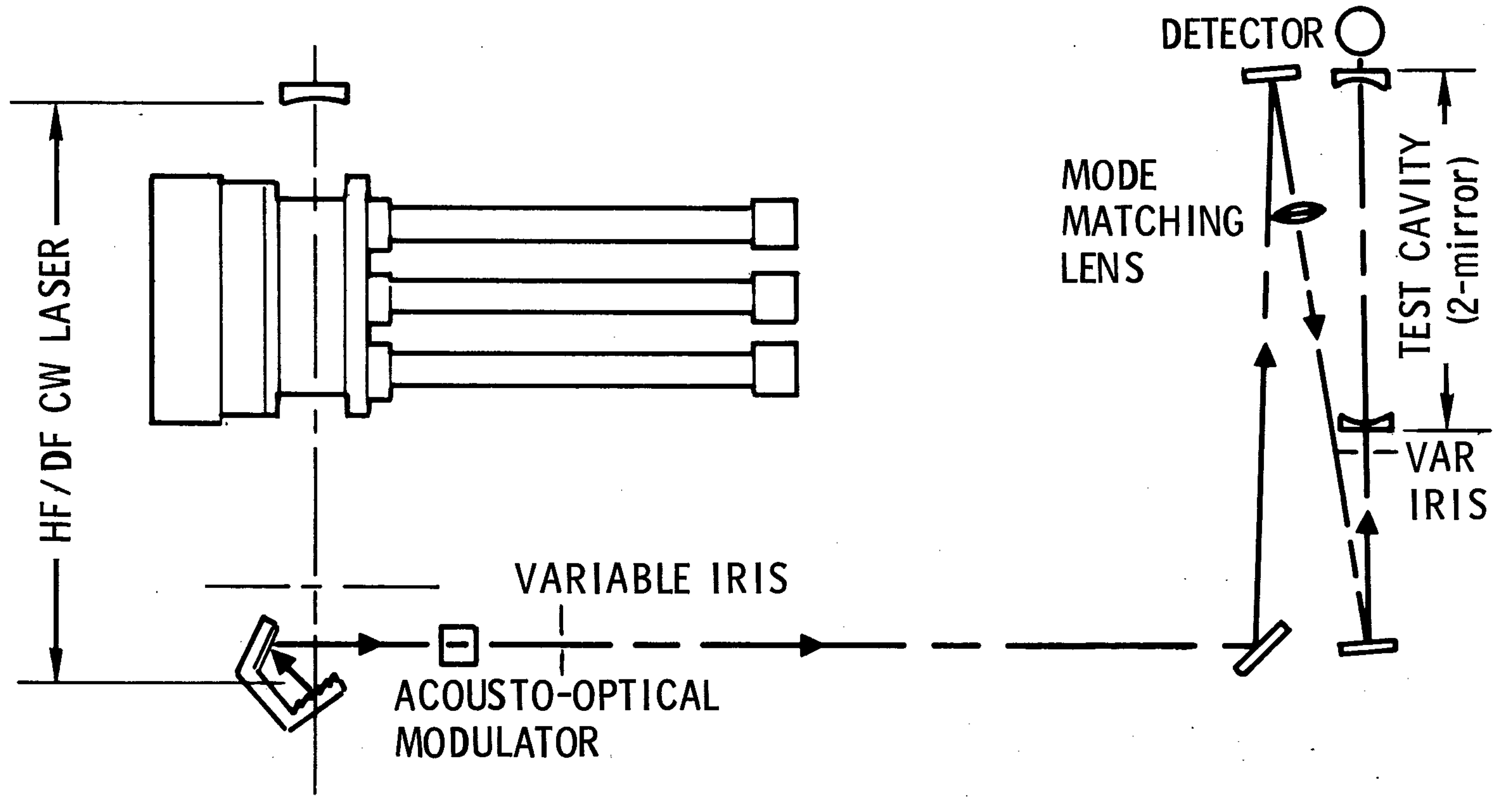

Fig. 2. Schematic of the Optical Layout for Demonstration of CAPS Method at Mid-Infrared Wavelengths

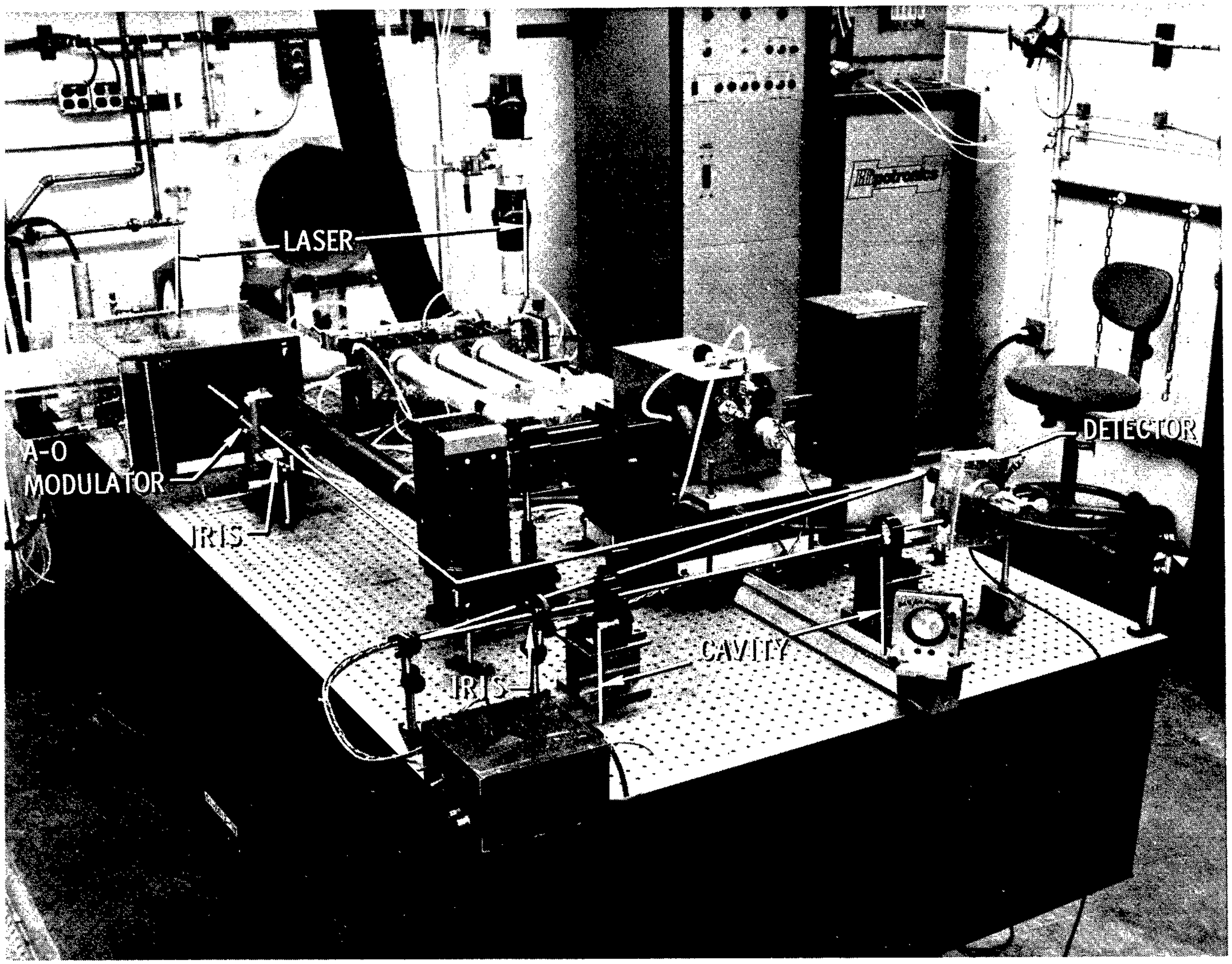

Fig. 3. The Optical Layout for Demonstration of CAPS Method at Mid-Infrared Wavelengths

III. RESULTS

Demonstration of a reflectance measurement was successfully performed, as shown in Fig. 3. In these measurements the HF beam has been linearly polarized by the Brewster angle windows. This polarization is preserved in the acousto-optic modulator, which requires linearly polarized radiation for efficient operation. The I_1 beam, the diffracted beam from the modulator, has not been particularly mode-matched into the test cavity. In such a situation, the cavity itself serves as a mode selector, since higher order transverse modes have shorter cavity lifetimes, and one adjusts the cavity for longest possible lifetime (i.e., largest observable phase shift). For reflectances of 0.99 or lower, past studies have shown no great errors. In any case, the observation will provide a lower-bound result. Measurements of tan Φ at several modulation frequencies were made over several days. Such repeatability provides an indication of the possible precision of the method. Earlier work (Refs. 1, 2) suggests even more precise figures if the noise problems discussed below are resolved.

A least-squares straight-line fit of the data through the origin produces a slope which yields a result of 0.9916 ± .0050 when the reflectances of both mirrors are assumed equal.

Even for the $P_2(8)$ line, a slight correction for water vapor absorption is necessary, assuming typical 50% humidity. From recent studies of HF laser line propagation through the atmosphere (Ref. 6), the absorption coefficient at $P_2(8)$ has been found to be $4.1 \times 10^{-4}\ \mathrm{cm}^{-1}(\mathrm{atm}\ H_2O)^{-1}$. At 50% humidity for the 72°F room, the amount of water vapor present is around 10 Torr or 1.3×10^{-2} atm. For a cavity length of 74.3 cm, the absorption A is 4×10^{-4} for a single pass within the cavity. For such small absorptions or high transmittances

$$\tan \phi = \frac{4\pi f L}{C} \left[\frac{R_1(1 - A)^2 R_2}{1 - R_2(1 - A)^2 R_2}\right]$$

and for reflectances close to unity, this leads to a linear adjustment. The final estimate of reflectance becomes 0.9920 ± 0.0050. This value is 0.3% smaller than the quoted manufacturer's reflectance of 0.9952 immediately at fabrication. The manufacturer's measurement was made using a single beam spectrophotometer and a nominal standard gold mirror.

The agreement is excellent. The slight discrepancy can be due to coating deteriorations common in this region or dirty coatings, since no attempts at special cleanings were made after delivery. The lower-bound discrepancy can also be slight transverse mode mismatch between the beam and the test cavity, as noted above.

A transmittance measurement on one mirror gives 9.1×10^{-5}. The remainder of the sum from unity (1-R-T) is 0.0079, which represents reflectance from the AR coating and also absorption and small-angle scattering within the substrate-coatings system. It is typical of coatings in this wavelength regime that the nonreflecting component is predominantly absorption/scattering. Coatings with significant amounts of absorption may pose potential problems at the high flux levels of high-power lasers. The spatial resolution in these demonstration experiments has not been optimized. Conventional empty, passive-cavity calculations for the TEM_{00} transverse mode shows the current spatial resolution to be 3 mm in diameter. This dimension is taken at the e^{-1} point of the hypothetical Gaussian intensity profile, within which is contained over 90% of the flux. Resolutions of better than 0.4 mm can easily be obtained if the test cavity is in a near-semiconcentric configuration.

The uncertainties depicted in Fig. 4 represent relatively large uncertainties in phase angle between $\pm 5°$ and $\pm 10°$. Some observed signals were observed to be noisier than others even after some signal averaging and smoothing by the lock-in amplifier. These fluctuations are attributed to fewer active longitudinal modes being available in longer wavelength infrared gas lasers for a given cavity length. These active modes must be matched a sufficient number of times per second with the longitudinal modes of the test cavity. Hitherto, in work at shorter wavelengths, cw gas lasers with wider gain spectral linewidths and cavities with longer lengths from 100-200 cm or

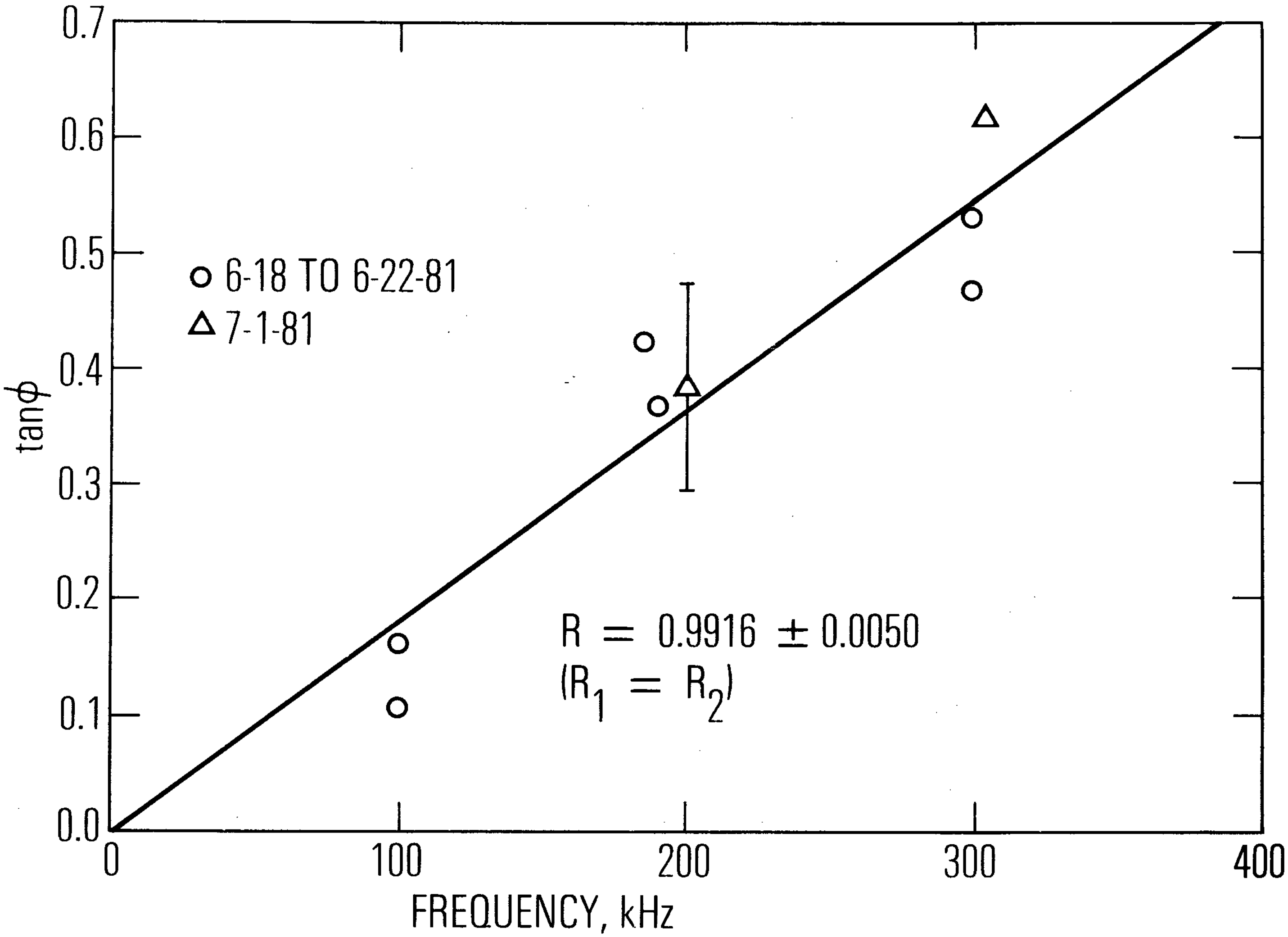

Fig. 4. Plot of tan ϕ vs. Modulation Frequency f for Mirrors at 2.911-μm Wavelength. The slope of the straight line yields a reflectance measurement

more were used (Refs. 1 and 2). As shown in Table 1, the relevant gain linewidth is usually narrower with increasing wavelengths because it corresponds to the Doppler width of the gas laser medium, which is proportional to spectral frequency (or inversely proportional to wavelength). Consequently, for a given transverse mode, fewer active or lasing longitudinal modes occur until an infrared gas laser is running virtually single mode for conventional cavity lengths.

The number of longitudinal modes available within the passive test cavity with the range of the active laser modes can also be calculated using $\Delta\nu_{\ell}$ = C(2L).[1] For a fixed 100-cm test cavity, the number of modes will also diminish. The product of laser modes and test cavity modes gives a relative figure for the number of dynamic mode matches per second. The dynamic mode matching on the microsecond time scale allows for no cavity stabilization requirements in this method. The temporal jitter in a cavity is due mainly to small changes in cavity length or mirror movement. Once the radiative flux of a particular frequency of a lasing mode is "matched" or "captured" into the test cavity, the flux frequency will follow that of the matched test cavity mode as changes occur because of Doppler shifts at the moving mirrors. The phase measurement is made on the 0.1-second time scale with a large number of integrated, averaged mode matches. In the HF and DF laser regimes, Table 1 shows that either cavity lengths must be lengthened or the number of mode coincidences enhanced. We have previously shown that dithering the cavity length will significantly stabilize the signal.

Table 1. Mode Matching Prospects

Laser	λ (μm)	Laser Gain Bandwidth (MHz)	Laser Longitudinal Modes A	100 cm Test Cavity Longitudinal Modes B	A–B
He-Ne[1]	0.633	1200	3	10	30
Dye[1] (CR599)	0.874	1.3×10^5	100	1000	10^5
HF (100 cm)	2.9	300	2	2	4
DF (100 cm)	3.9	225	1-2	1-2	1-4

IV. OUTLOOK

The CAPS method is unique in that the accuracy improves with increasing reflectance. This behavior is illustrated in Fig. 5 for Φ around 45° and uncertainties of ±5°. If HF or DF mirrors with reflectances at 0.999 or better are produced, this method can easily achieve the Air Force target specification of ±.0010 for high-energy lasers.

In the case of mirrors with opaque, nontransmitting cavities, the reflectance R_3 for s or p linear polarizations can be examined at a number of angles of incidence up to 45° and beyond. The laser source beam must then be correctly polarized to make the s or p linear polarization measurement. Currently, exploratory work is proceeding on this concept (Ref. 7) using the He-Ne laser at 0.63-μm wavelength.

It is also quite apparent that a mirror with superior reflectance, R_3, can be tested in a three-mirror cavity with mirrors of known reflectances, R_1 and R_2. In Fig. 6 R_1 and R_2 are assumed to be 0.99 while the unknown R_3 is varied from 0.98 up to unity. The range in phase shift ϕ is quite substantial and provides for a good measure of R_3. The accuracy of determining R_3 will be about the same as that for R_1 and R_2.

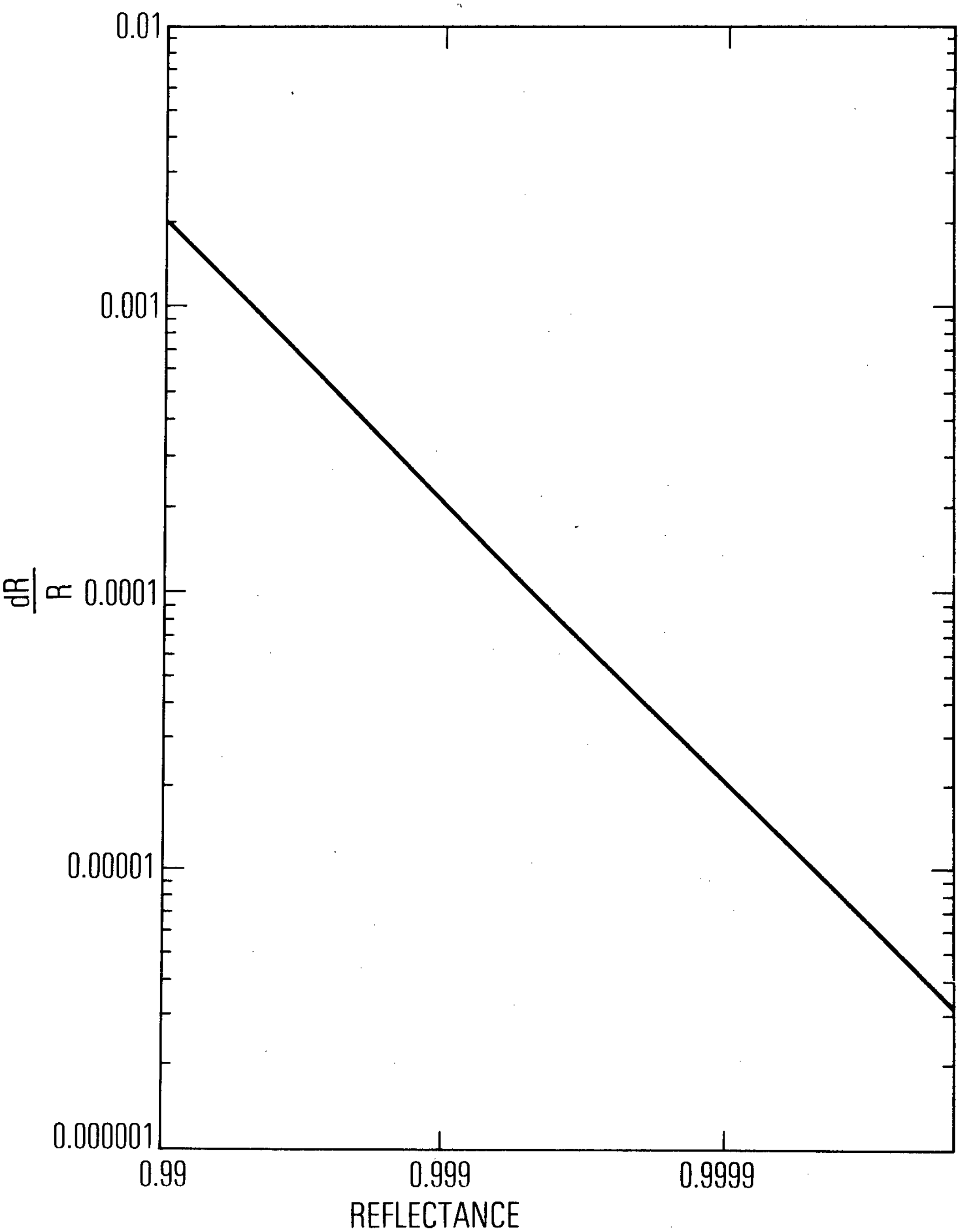

Fig. 5. Improving Accuracy with the CAPS Method as Reflectance Improves

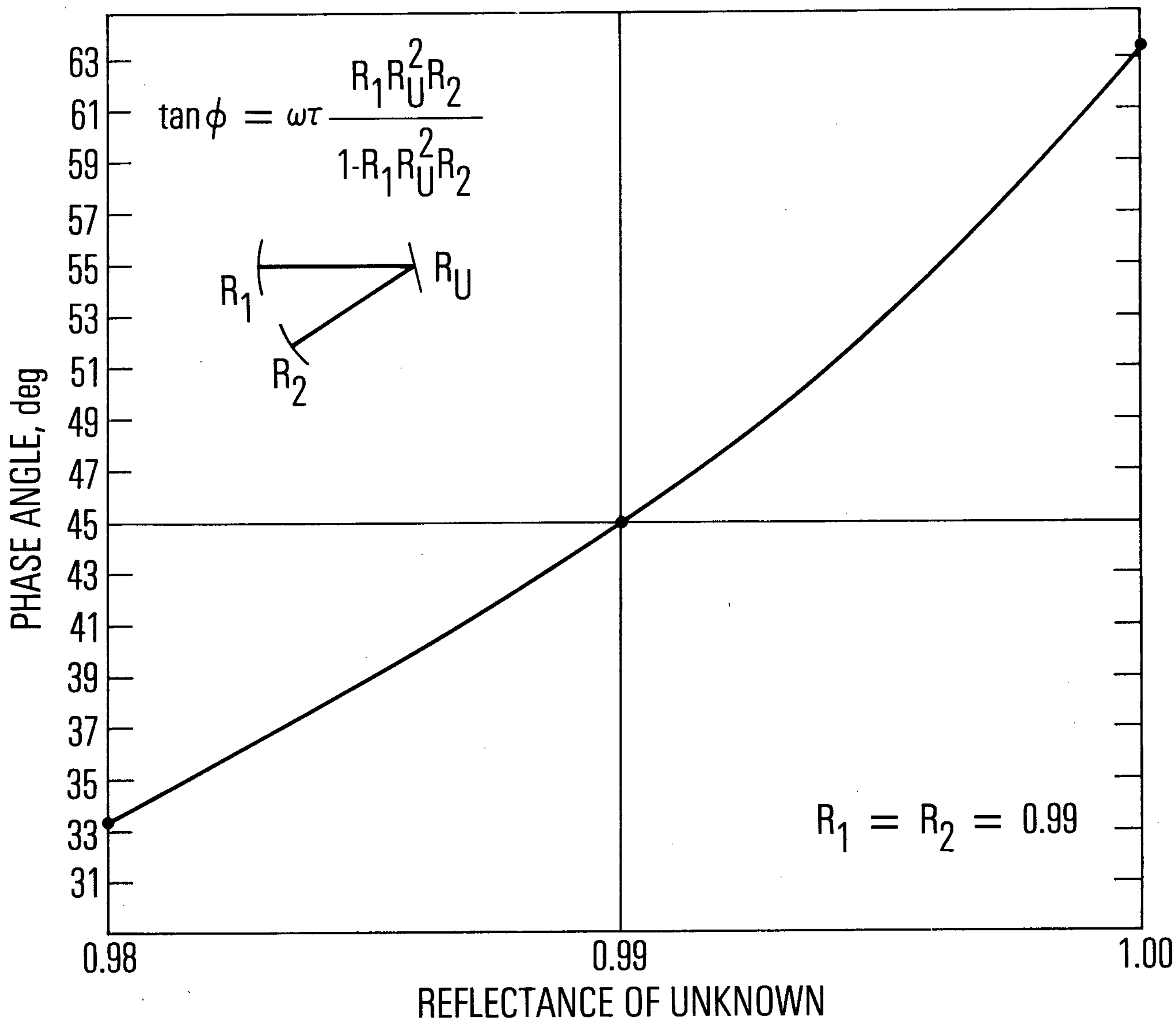

Fig. 6. Measurement of a Mirror with Superior Unknown Reflectance in a Three-Mirror Cavity

V. CONCLUSIONS

A high-reflectance measurement using the Cavity Phase Shift method has been successfully performed at HF wavelengths. Key improvements to the method for its use in the mid-infrared region may include an intracavity chamber for absorption control and a test cavity dither to stabilize mode matching. The use of the intracavity chamber will also permit studies of propagation or atmospheric attenuation as well as studies of the gradual degradation of coatings in specified adverse environments. The method appears to be a strong prospect in supporting coating development studies.

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